BNL-69312

Effects of p/n Inhomogeneity on CdZnTe Radiation Detectors

M. Chu,* S. Terterian, D. Ting, R.B. James,[a] M. Szawlowski,[b] and G.J. Visser[c]

Fermionics Corporation
4555 Runway St, Simi Valley, CA 93063

[a] Brookhaven National Laboratory; [b] Advanced Photonix, Inc.; [c] Nova R&D, Inc.

ABSTRACT

Spectrometer grade, room-temperature radiation detectors have been produced on $Cd_{0.90}Zn_{0.10}Te$ grown by the low-pressure Bridgman technique. Small amount of indium has been used to compensate the uncompensated Cd vacancies for the crystals to be semi-insulating. The properties of the detectors are critically dependent on the amount of excess Te introduced into the growth melts of the $Cd_{0.90}Zn_{0.10}Te$ crystals and the best detectors are fabricated from crystals grown with 1.5% excess Te. Detector resolution of ^{57}Co and ^{241}Am radiation peaks are observed on all detectors except the ones produced on $Cd_{0.90}Zn_{0.10}Te$ grown from the melt in the stoichiometric condition. The lack of resolution of these stoichiometric grown detectors is explained by a p/n conduction-type inhomogeneity model.

Keywords: CdTe, CdZnTe, Radiation Detectors, Gamma Ray Detectors, Defects, Te Antisites.

1. INTRODUCTION

CdTe and CdZnTe (CZT) have been considered to be promising semiconductors for producing room temperature radiation detectors for decades.[1] However, the only high quality room-temperature CdTe/CZT detectors are fabricated from $Cd_{0.80}Zn_{0.20}Te$ grown under a high pressure condition.[2] In this paper, we report the properties of spectrometer grade $Cd_{0.90}Zn_{0.10}Te$ detectors produced on low-pressure grown crystals. The detector testing results as a function of excess Te in the crystal growth melts are described in Section 2. The poor resolution of detectors fabricated from crystals grown from stoichiometric melts is explained by an inhomogeneity model in Section 3.

2. EXPERIMENTAL RESULTS

In this study, five groups of $Cd_{0.90}Zn_{0.10}Te$ crystals were respectively grown by the low pressure Bridgman technique using melts with excess Te in the amounts of 0.0, 1.0, 1.5, 2.0, and 3.0 atomic percent. Without impurity doping, all of these crystals are p-type, which is the result of net acceptors of Cd vacancies after the compensation of acceptors of Cd vacancies by the shallow donors of singly ionized Te antisites.[3] To produce CZT with high resistivities, crystals in each of the above five groups were doped with indium (shallow donors) in different quantities until a high resistivity crystal was obtained. The amount of indium required for producing high resistivity CZT needs to be controlled very precisely. The reproducibility of the high resistivity is about 75%.

The indium concentration introduced into the crystals for achieving a high resistivity for each of the five groups is shown in Table I. The data clearly shows that the indium density needed for obtaining a high resistivity crystal is proportional to the magnitude of the excess Te in the crystal growth melt. For Crystal 9294, grown without excess Te, a very low indium concentration on the order of $2x10^{14}$ cm^{-3} is sufficient to compensate the residual Cd vacancies to achieve a high resistivity. As the amount of excess Te increases, more indium is required for compensating the residual Cd vacancies. This phenomenon indicates that a CZT crystal has more net Cd vacancies as the crystal is grown with more excess Te.

* E-mail: M.Chu@Fermionics.com

Table I. Properties of $Cd_{0.90}Zn_{0.10}Te$ crystals and detectors as a function of excess Te in crystal growth melt. "**X**" denotes "not resolved."

Stoichiometry (Te/(Cd+Zn))	1.000	1.010	1.015	1.020	1.030
Crystal Log #	9294	9489	9872	9618	9238
Resistivity (Ω·cm)	10^8	10^8	$\geq 10^9$	$\geq 10^9$	$\geq 10^9$
Indium-doping (cm^{-3})	2.1×10^{14}	3.3×10^{15}	2.5×10^{15}	6.4×10^{15}	1×10^{16}
^{57}Co 122 keV Peak	X	Resolved	6.0 keV	13.4 keV	Resolved
^{57}Co 136 keV Peak	X	X	Resolved	Resolved	Resolved
FWHM of ^{241}Am @ 59.5 keV	X	Resolved	3.6 keV	6.5 keV	6.6 keV
Np-L, Te-K, Cd and Te Escape Peaks From ^{241}Am	X	X	Resolved	X	X

Radiation detectors, with sizes between 4x4x1 mm^3 and 5x5x3 mm^3, were fabricated in wafers from each of the five crystals listed in Table I and were subsequently tested using radiation sources of ^{57}Co and ^{241}Am. The testing results are also summarized in Table I. Evidently, the $Cd_{0.90}Zn_{0.10}Te$ detector performance critically depends on the amount of excess Te added into the crystal growth melts. The detectors fabricated from Crystal 9294, which was grown without excess Te, cannot resolve any of the radiation peaks of ^{57}Co and ^{241}Am. Instead, a random broad peak was observed. A ^{57}Co spectrum measured by these detectors is shown in Figure 1. This observation is consistent with the fact that there is no reported room-temperature detection result on detectors fabricated in CZT/CdTe grown without excess Te.

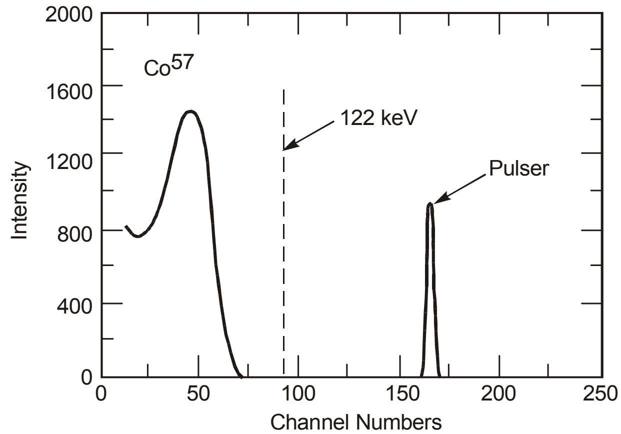

Figure 1. Spectrum of ^{57}Co measured by detectors (4x4x1 mm^3, 100V) from CZT 9294.

The detectors from Crystal 9489, which was grown with 1% excess Te, have better performance and can resolve the ^{57}Co 122 keV and ^{241}Am 59.5 keV peaks. The best detectors among those listed in Table I are fabricated from CZT 9364, a crystal grown with 1.5% excess Te. The ^{241}Am and ^{57}Co spectra measured by these detectors are shown in Figures 2 and 3, respectively. In addition to the ^{57}Co 122 keV, ^{57}Co 136 keV, and ^{241}Am 59.5keV peaks, the detectors can also resolve the six ^{241}Am low energy Np-L, Te-K, Cd-escape, and Te-escape peaks. Besides, the full widths at half maximum (FWHM) of the ^{57}Co 122 keV and ^{241}Am 59.5keV peaks have very low values of 6.0 keV and 3.6 keV, respectively.

When more than 1.5% excess Te is introduced into the CZT growth melt, detectors with the capability of resolving the radiation peaks can still be produced from the grown crystal; but the performance of the detectors begin to degrade. As shown in Table I, the degree of degradation is proportional to the amount of the excess Te used for the CZT growth. Detectors from CZT 9618, which were grown with 2.0% excess Te, can resolve the major ^{57}Co and ^{241}Am peaks. The values of the FWHMs of the ^{57}Co 122 keV and ^{241}Am 59.5keV peaks are still respectable. But the detectors can detect only the envelop of the low energy ^{241}Am 59.5keV peaks instead of the individual ones. The characteristics of detectors from CZT 9238, a crystal grown with 3.0% excess Te, are even worse. There is a broad shoulder to the left side of the ^{57}Co 122 keV peak, a typical sign of high hole trapping. As a result, a meaningful FWHM value of this peak cannot be measured.

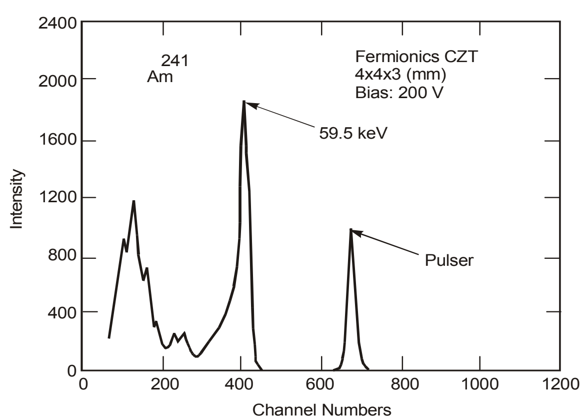

Figure 2. Spectrum of ^{241}Am measured by a detector from CZT 9872.

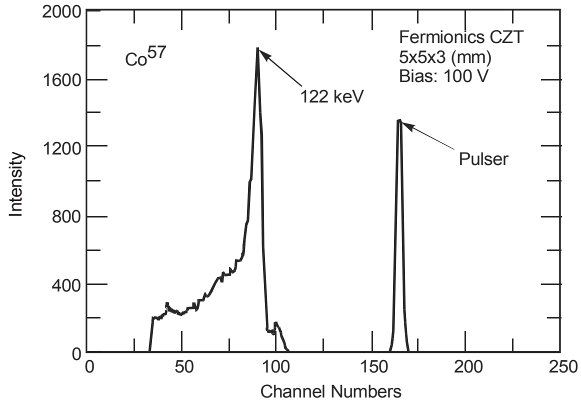

Figure 3. Spectrum of ^{57}Co measured by a detector from CZT 9364

3. DISCUSSIONS

The discussion of the general properties of the detector results in Table I will be published elsewhere. In this paper, the discussion will be focused on detectors from CZT 9294. The ^{57}Co spectrum measured by these detectors from is shown in Figure 1. None of the characteristic ^{57}Co peaks is observed. Instead, there is a broad peak with energy much lower than the 122 keV. To understand the cause of such results, a separate experiment was conducted. Several detectors from CZT 9294 and CZT 9364 were exposed to visible light and the DC and low frequency photocurrent from each detector was measured. All detectors from CZT 9294 have photocurrents more than twenty times higher than those measured on the well-behaved detectors from CZT 9364. How can CZT 9294 detectors that cannot resolve gamma ray peaks show such peculiar high photocurrents to visible light? For such high currents, the hole lifetime in CZT must be higher than an unheard value of 20 μsec. To explain these results, a model[4] proposed on small bandgap, near intrinsic HgCdTe can be used.

In low carrier concentration (~10^{14} cm^{-3}) n-type HgCdTe with a cutoff wavelength of ~12 μm, extended p-type inclusions or domains are frequently observed.[5] Dislocations are a potential cause of the p-type domains. In near intrinsic n-type material, a small amount of acceptor impurities or defects (≥$1\text{x}10^{14}$ cm^{-3}) diffused through dislocations can easily convert the neighborhood of the dislocations to p-type. The symptoms of such a structure are a higher than normal DC and low frequency photocurrent in photoconductors larger than 1 mm, and an unreasonably high measured hole lifetime. The model[4] developed to explain these phenomena states that the extended p-type domains in the n-type matrix form a potential well for holes. When the p-type domains form a network connected to the cathode, a new mechanism to collect the holes is formed: the photo-generated holes in the n-type matrix can drift into the potential well and be collected. This process is illustrated in Figure 4. In a conventional n-type HgCdTe photoconductor with no p-type domain, as shown in Figure 4(a), holes that can be collected by the cathode must be generated within a distance of $l_h=\mu_h\tau_h E$ from the cathode, where μ_h is the hole mobility, τ_h is the hole lifetime, and E is the electric field. But in n-type HgCdTe with networked p-type domains connected to the cathode, the situation is different. Since the holes in the p-type potential well have fewer electrons to recombine with, they can have a very long apparent (measured) lifetime (τ_h^{in}) and drift for a very long distance l_h^{in}, where "in" denotes "inhomogeneity". Consequently, as shown in Figure 4(b), holes generated by the photons outside the l_h range from the cathode can still be collected by drifting into the p-type domains and then to the cathode. As a result, the photoconductor can collect a higher photocurrent. It is noted though that the detectivity of such detectors actually suffers because the detector leakage current and noise are very high.

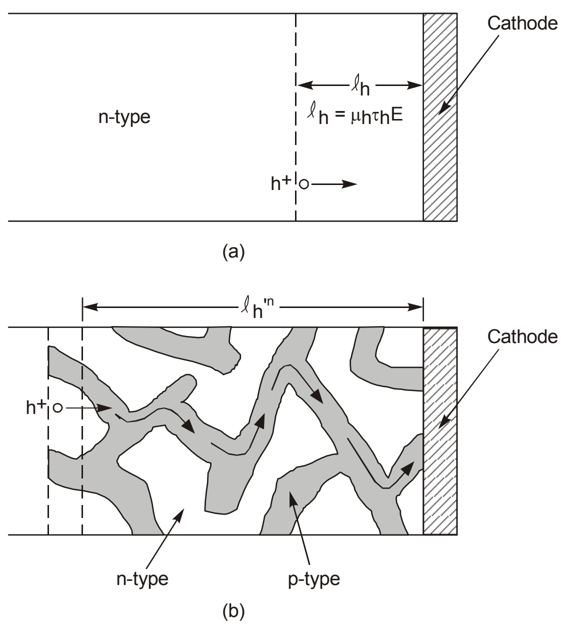

Figure 4. Modeling of DC collection of photo-generated holes in near intrinsic n-HgCdTe: (a) homogeneous condition, and (b) inhomogeneous condition with p-networks in n-matrix.

The phenomenon of the peculiar high photocurrent in response to visible light observed on detectors from CZT 9294 is similar to the excess high photocurrent and unreasonable high carrier lifetime found on the HgCdTe photoconductors with p/n inhomogeneity. According to the model explained by Figure 4, CZT 9294 may also have networked p-type domains in an n-type matrix. This idea is consistent with the fact that CZT 9294 was grown from stoichiometrc melt. Comparing CZT 9294 with other crystals in Table I, this crystal has the least amount of Cd vacancies and Te antisites, the defects been proposed as the deep levels to pin the Fermi level to the center of the bandgap. According to Ref. 5 and 6, it is impossible to achieve homogeneous high resistivity simply by close compensation between shallow donors and acceptors. Any slight fluctuation of the densities of acceptors and donors can cause conduction-type inhomogeneity. For achieving high resistivity, a semiconductor must have sufficient impurities or defects with a deep level near the middle of the bandgap to pin the Fermi level to it. Based on the above discussion, it becomes clear that the density of deep level Te antisites or Cd vcacancies in CZT 9294 has reached such a low level that p-type networks has formed in the n-type matrix.

The concept of conduction-type inhomogeneity can be used to well explain the measured gamma ray spectrum shown in Figure 1. The model of this explanation is illustrated in Figure 5. During the measurements, the shaping time (t_s) is typically 1-2 μsec and is comparable to the hole lifetime τ_h. In a detector without conduction-type inhomogeneity, the holes generated in a distance of $l_h(t_s) = \mu_h t_s E$ from the cathode are collected within the shaping time after receiving a gamma ray photon. However, in a detector with networks of p-domains in n-matrix, many holes are collected by first drifting from the n-matrix to branches of the p-domains, and then to the cathode. Since in the p-type networks the holes travel through zigzag channels, and the maximum hole traveling distance is $l_h(t_s)$, the holes that can be collected in the shaping time t_s after a gamma ray photon reaches the detector are then in a distance of l_h' from the cathode, which is shorter than the distance of $l_h(t_s)$. As a result, detectors from CZT 9294 collect much less holes in t_s than a homogeneous detector does in the same time period, and will consider the incident gamma ray to have a lower energy than it actually has. Furthermore, in the following shaping time periods, even if there is no incident gamma ray, holes generated by the original gamma ray in the area beyond the distance of l_h' from the cathode are still collected through the p-channels. As a result, when a detector from CZT 9294 receives 122 keV gamma ray photons, the electronics does not register single gamma ray photons with this energy. Instead, it registers a number of low energy gamma ray photons. Thus, Figure 1 curve is formed and no characteristic ^{57}Co peak is observed.

The relationship between l_h' and $l_h(t_s)$ can be approximated by considering the averages of these parameters. Assuming l_p is the average distance the holes travel in the p-channel in t_s, then

$$l_h' = \alpha\, l_p \tag{1}$$

where α is a constant less than 1. Let E′ be the average electric field in the p-channel along the velocity of the holes and E be the electric field in Figure 5(a), then

$$E' = \alpha E \tag{2}$$

Substituting $l_p=\mu_h t_s E'$ and Eq.2 to Eq.1, and use $l_h(t_s) = \mu_h t_s E$,

$$l_h' = \alpha^2 l_h(t_s) \tag{3}$$

Since the orientation of each branch of the p-channel is random, the average orientation of l_p can be approximated to be 45° from the orientation of l_h', and α becomes cos45°. Then, Equation (3) becomes

$$l_h' = l_h(t_s)/2 \tag{4}$$

In homogeneous CZT detectors, most of the holes contributed to the 122 keV peak in a ^{57}Co spectrum are generated and collected in the region within the distance of $l_h(t_s)$ from the electrode. Now, in the inhomogeneous CZT detectors, these holes are still generated in this region, but they will be collected in two consecutive shaping times because of Equation 4. Therefore, it is expected that in the spectrum of inhomogeneous detectors, the ^{57}Co 122 keV gamma ray will register near 61 keV. And this is exactly what is observed in Figure 1. Naturally, for different degree of inhomogeneity, the ^{57}Co peak will shift accordingly.

The model described by Figure 5 presents the hole "trapping" effect. By the same argument, the "trapping" effect applies to electrons too. Here, Figure 5 discussed the "trapping" mechanism by the extended routs for holes and electrons to travel. Another massive trapping mechanism in the p/n inhomogeneity is the trapping of carriers by isolated potential wells, which can be easily understood and doesn't need to be elaborated.

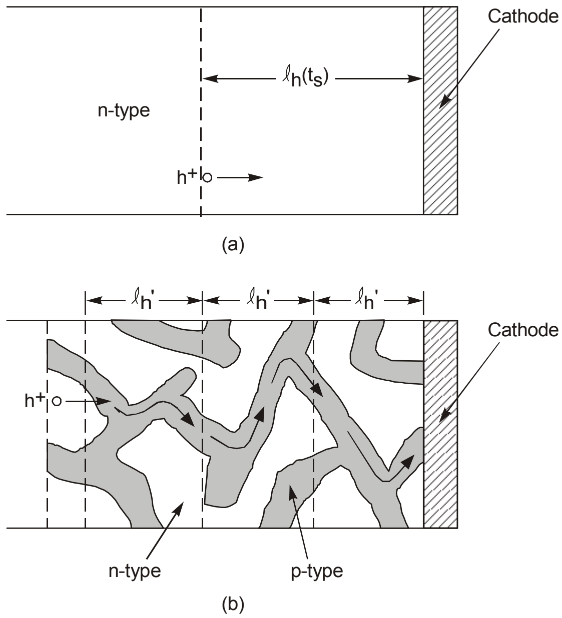

Figure 5. Modeling of gamma ray spectral response by CZT detectors
In (a) homogeneous condition, and (b) inhomogeneous condition with
p-networks in n-matrix.

4. SUMMARY

In summary, Spectrometer grade, room-temperature radiation detectors have been produced on $Cd_{0.90}Zn_{0.10}Te$ grown by the low-pressure Bridgman technique. Small amount of indium has been used to compensate the uncompensated Cd vacancies for the crystals to be semi-insulating. The properties of the detectors are critically dependent on the amount of excess Te introduced into the growth melts of the $Cd_{0.90}Zn_{0.10}Te$ crystals and the best detectors are fabricated from crystals grown with 1.5% excess Te. Detector resolution of ^{57}Co and ^{241}Am radiation peaks are observed on all detectors except the ones produced on $Cd_{0.90}Zn_{0.10}Te$ grown from the melt in the stoichiometric condition. The lack of resolution of these stoichiometric grown detectors is explained by a p/n conduction-type inhomogeneity model. Because of the lack of excess Te, such crystals do not have sufficient Cd vacancies and Te antisites, the deep level species, to pin the Fermi level to the middle of the bandgap. As a result, p-type domains in n-type matrix or vice versa are formed. Such inhomogeneity causes trapping of electrons and holes and results in detectors with no capability to resolve radiation peaks.

ACKNOWLEDGEMENT

This work was partially supported by the Defense Threat Reduction Agency under Contract No. DTRA01-01-C-0071.

REFERENCES

1. Proceedings of the Second International Symposium on Cadmium Telluride: Physical Properties and Applications, Strasbourg (1976)
2. Proceedings of SPIE on "Hard X-ray, Gamma-Ray, and Neutron Detector Physics," Vol. 3768, (1999)

3. M. Chu, S. Terterian, D. Ting, C.C. Wang, H.K. Gurgenian, and S. Mesropian, Appl. Phys. Lett. 79, 2728 (2001).
4. A conclusion of discussions between M. Chu from Fermionics Corporation and a group of scientists from Santa Barbara Research Center (currently Raytheon Infrared Operations) led by C.Y. Hwang, 1992.
5. A.G. Thompson, J. Electron. Mater. 2, 47 (1973)
6. M. Fiederle, C. Eiche, M. Salk, R. Schwarz, K.W. Bens, W. Stadler, D.M. Hofmann, and B.K. Meyer, J. Appl. Phys. 84, 6689 (1998)